A Time Series of Photo-synthetically Available Radiation at the Ocean Surface from SeaWiFS and MODIS Data

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ABSTRACT

A global, 13-year record of photo-synthetically available radiation (PAR) at the ocean surface (9-km resolution) has been generated from SeaWiFS, MODIS-Aqua, and MODIS-Terra data. The PAR values are essentially obtained by subtracting from the solar irradiance at the top of the atmosphere (known) the solar energy reflected by the ocean-atmosphere system (satellite-derived) and absorbed by the atmosphere (modeled). Observations by individual instruments, combinations of two instruments, and three instruments are considered in the calculations. Spatial and temporal biases between estimates from one, two, or three instruments are determined and corrected, resulting in a consistent time series for variability studies. Uncertainties are quantified on daily, weekly, and monthly time scales for the various instrument combinations from comparisons with in situ measurements. The correlative behavior of PAR, sea surface temperature, and chlorophyll concentration in the Equatorial Pacific is examined. PAR monitoring will continue with current and future satellite ocean-color sensors, in particular VIIRS, and the methodology will be extended to generating UV-A and UV-B irradiance.

Keywords: Photosynthetically available radiation, remote sensing, ocean color, phytoplankton, SeaWiFS, MODIS

1. INTRODUCTION

The solar energy available for aquatic photosynthesis, known as photo-synthetically available radiation (PAR), controls the growth of phytoplankton and, therefore, regulates the composition and evolution of marine ecosystems. Knowing the spatial and temporal distribution of PAR over the global oceans is critical to understanding biogeochemical cycles of carbon, nutrients, and oxygen, and to address important climate issues such as the fate of anthropogenic atmospheric carbon dioxide. Sunlight in the PAR spectral range also contributes to warming the upper ocean, modifying the density contrast between the mixed layer and deeper layers. The resulting variations in the depth and temperature of the mixed layer play a major role in the physical climate.

In view of this, a time series of daily PAR at the ocean surface has been generated from SeaWiFS, MODIS-Terra, and MODIS-Aqua data. The product covers the global oceans at a spatial resolution of about 9x9 km and starts on September 1997, i.e., at the beginning of the SeaWiFS operational phase. A mature algorithm, originally developed to estimate daily PAR from SeaWiFS data (Frouin et al., 2003), has been adapted/modified to include data from multiple ocean-color sensors. Combining data from satellite sensors with different equatorial crossing times takes into account the diurnal variability of clouds, the chief limitation when using data from a single sensor in polar orbit (typically one observation per day). The advantage of using ocean-color sensors to estimate PAR is that they provide chlorophyll concentration, another key parameter in ocean primary productivity modeling. Furthermore, the same data pre-processing is required, i.e., PAR can be produced with little extra effort. In this way, studies of ecosystem dynamics are facilitated.

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Consistency across time is achieved by comparing estimates obtained using data from one or two sensors with those from the three sensors when they are all operating, determining adjustment factors, and applying those factors to reduce biases during the periods with only one or two sensors. Accuracy is quantified on daily, weekly, and monthly time scales against existing in-situ measurements, and continues to be monitored using long-term PAR sensors installed at selected sites. Eventually, the algorithm will be refined, and the time series re-processed.

The NASA Ocean Biology Processing Group (OBPG) accomplishes large-scale production and makes the PAR time series and related documents available to the public from their web site. The processing system, including routine check of accuracy and control of quality, is designed to accommodate, in addition to SeaWiFS and MODIS, future sensors with ocean-color capabilities.

In the present article, after describing the PAR algorithm and computational procedures, we report on product evaluation, i.e., comparisons with in situ measurements. We document the consistency checks and adjustments performed to generate a consistent time series from multiple sensors. We provide evidence, using typical examples, that accuracy on a daily time scale is improved when using several sensors. Next we examine the variability in the time series and present a correlative analysis of PAR, sea surface temperature, and chlorophyll concentration in the Equatorial Pacific. Finally we conclude with a perspective on future work, including extending the methodology to compute UV-A and UV-B irradiance.

2. SATELLITE ESTIMATION

2.1 Objective

The objective is to produce a long-term, consistent time series of daily PAR over the global oceans from multiple satellite ocean-color observations (SeaWiFS, MODIS-Aqua, MODIS-Terra, etc.). Since photo-system processes are quantum reactions, PAR is defined as the quantum energy flux from the Sun in the spectral range 400-700 nm. It is expressed in Einstein/m^2/day. Daily PAR is the average flux during a day (24 hours).

2.2 Approach

The approach is to estimate PAR on a pixel basis from individual satellite instruments and orbits, then merge the individual estimates. For each instrument, PAR is computed as the difference between the incident solar flux between 400 and 700 nm (known) and the reflected flux (measured), taking into account atmospheric absorption (modeled). Knowledge of pixel composition is not required, eliminating the need for cloud screening and arbitrary assumptions about sub-pixel cloudiness.

2.3 Model

The PAR model uses plane-parallel theory and assumes that the effects of clouds and clear atmosphere can be de-coupled. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer, and surface PAR is expressed as the product of a clear-sky component and cloud transmittance. The strength of such a de-coupled model resides in its simplicity. Importantly, it is not necessary to distinguish between clear and cloudy regions within a pixel. The solar flux reaching the ocean surface is given by

$$E = E_{clear}(1 - A)(1 - A_s)^{-1} \tag{1}$$

where A is the albedo of the cloud-surface system and A_s the albedo of the surface, and E_{clear} is the solar flux that would reach the surface if the cloud/ surface system were non reflecting and non absorbing. A is expressed as a function of the radiance measured by the satellite sensor in the PAR spectral range. Details about the model are provided in Frouin and Chertock (1992), Frouin et al. (2003), Frouin and Murakami (2007), and Frouin and McPherson (2012).

2.4 Procedure

A daily PAR estimate is obtained for each instantaneous pixel, assuming the cloud/surface system is stable during the day and corresponds to the satellite observation. Daily PAR estimates obtained separately from different orbits and individual sensors are binned using a simple, linear averaging scheme (arithmetical mean), or by weighting the estimates using the cosine of the solar zenith angle. Since MODIS-Terra, SeaWiFS, and MODIS-Aqua cross the Equator at different local times (i.e., 10:30, 12:00, and 13:30) the diurnal variability of clouds is taken into account by averaging individual estimates. To ensure consistency of the PAR data over time, estimates using data from one, two, or three sensors are compared, and statistical adjustment factors determined.

3. EVALUATION AGAINST IN-SITU MEASUREMENTS

We have analyzed PAR data collected during 2005-2010 at the COVE site off Chesapeake Bay in the North Atlantic and made comparisons with the estimates from SeaWiFS, MODIS-Aqua, and MODIS-Terra data. PAR is measured almost continuously at that site since 2003, but with 2 PAR sensors since 2005. Only the data collected concomitantly with the 2 PAR sensors, i.e., during 2005-2010, were used in the evaluation, which allowed good quality control of the data and efficient elimination of outliers. The resulting time series of in situ daily PAR data (average from the 2 PAR sensors) is displayed in Figure 1. LAC data from the satellite sensors were used to compute PAR and the estimates were interpolated to the COVE location to generate daily values. Individual estimates during the day were weight-averaged using the cosine of the sun zenith angle.

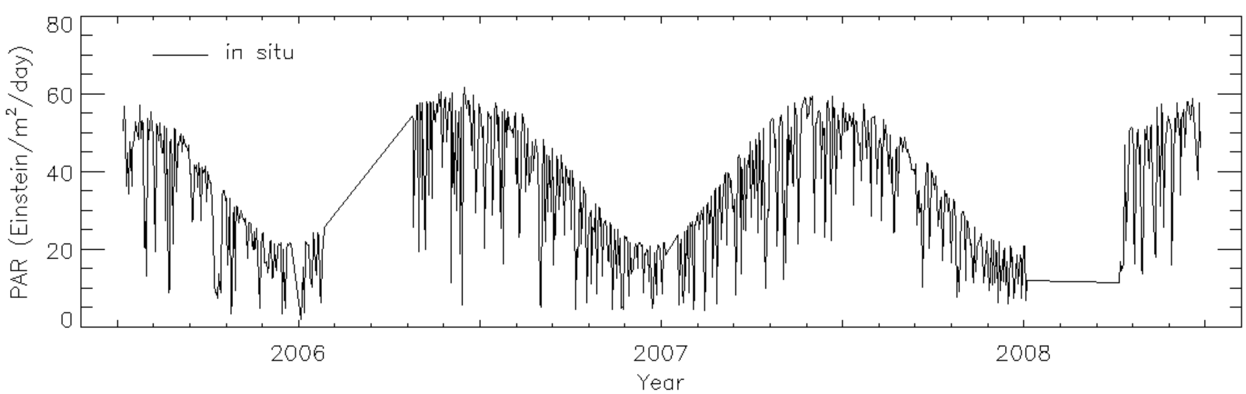


Figure 1*: Time series of daily surface PAR measured in situ (average of data from 2 PAR sensors) at the COVE site. Differences between the 2 PAR sensors are generally less than 1-2 E/m^2/d or 5%. (The COVE Team is gratefully acknowledged for maintaining the PAR sensors and making the data available.)*

Table 1 displays the performance statistics for SeaWiFS, MODIS-Aqua, and MODIS-Terra on daily, weekly, and monthly time scales. Compared with in situ measurements, the satellite estimates are higher by 1.8 to 2.8 E/m^2/d (5 to 8%), depending on the instrument and the time scale. RMS differences are significantly decreased when going from daily to monthly estimates, for example from 6.5 to 3.3 E/m^2/d for SeaWiFS. The biases may be explained by the fact that the time of satellite overpass is near local noon, late morning, or early afternoon, i.e., when cloudiness is generally reduced, and/or by an overestimation of the clear sky values.

For completely clear sky situations, The PAR estimates from the three instruments are in much better agreement with the measurements. They exhibit a small bias, of about 1 E/m2/d (about 2-3%), which is attributed to the accuracy of the clear sky model and the calculation of the spectrally integrated transmittance functions. There is a small seasonal variation in the ratio of satellite-derived and measured PAR values, with estimates larger during late summer and fall, which may be due to an underestimation of the aerosol optical thickness used in the PAR algorithm (aerosol properties are specified from climatology). From the analysis, and Since PAR is computed as the product of the clear sky value and the transmittance of the cloud/surface system, the PAR values may be corrected (reduced) by the following factors, 1.023 (SeaWiFS), 1.027 (MODIS-Aqua), and 1.030 (MODIS-Terra).

***Table 1**: Comparison statistics of estimated and measured surface PAR at the COVE site for daily, weekly, and monthly time scales. All situations (clear and cloudy) are used in the comparisons.*

Satellite(s)	Daily	Weekly	Monthly
SeaWiFS	$r^2 = 0.874$ Bias = 2.83 $E/m^2/d$ RMS Diff. = 6.49 $E/m^2/d$ Nb. Points = 1408	$r^2 = 0.931$ Bias = 2.65 $E/m^2/d$ RMS Diff. = 4.54 $E/m^2/d$ Nb. Points = 225	$r^2 = 0.968$ Bias = 2.25 $E/m^2/d$ RMS Diff. = 3.30 $E/m^2/d$ Nb. Points = 57
MODIS-Aqua	$r^2 = 0.857$ Bias = 1.85 $E/m^2/d$ RMS Diff. = 6.77 $E/m^2/d$ Nb. Points = 1582	$r^2 = 0.932$ Bias = 1.88 $E/m^2/d$ RMS Diff. = 4.22 $E/m^2/d$ Nb. Points = 265	$r^2 = 0.977$ Bias = 1.77 $E/m^2/d$ RMS Diff. = 2.85 $E/m^2/d$ Nb. Points = 63
MODIS-Terra	$r^2 = 0.883$ Bias = 2.31 $E/m^2/d$ RMS Diff. = 6.28 $E/m^2/d$ Nb. Points = 1596	$r^2 = 0.945$ Bias = 2.33 $E/m^2/d$ RMS Diff. = 4.25 $E/m^2/d$ Nb. Points = 265	$r^2 = 0.983$ Bias = 2.27 $E/m^2/d$ RMS Diff. = 3.23 $E/m^2/d$ Nb. Points = 63

In cloudy situations, combining observations by MODIS and SeaWiFS reduces the bias. This is illustrated in Figure 2, which shows some typical situations. For the two situations on the left side and middle of the figure, the SeaWiFS observation is made when the sky is quite clear, leading to PAR overestimation compared with in situ measurements. For the situation on the right side of the figure, the SeaWiFS observation, on the contrary, is made when the sky is cloudy, but the sky is clear during a large part of the day, resulting in a PAR underestimation compared with in situ measurements. Now if we combine MODIS-Aqua, MODIS-Terra, and SeaWiFS observations, the agreement with in situ measurements is much better (the cloud effect at the time of the MODIS-Aqua and MODIS-Terra observations was estimated from the in situ measurements).

Using the clear sky correction (see above), the comparison statistics of estimated and measured PAR were re-computed for individual instruments, two instruments in various combinations, and three instruments. Figure 6 displays results obtained with three instruments on daily, weekly, and monthly time scales. The performance is improved compared with that of individual satellites, with for example biases and RMS differences in monthly values reduced to 1.2 and 2.9 $E/m^2/d$, respectively (see Table 1 for comparison).

The remaining biases are likely due to the diurnal variability of cloudiness not fully accounted for in the algorithm. At the COVE site, a maritime non-convective location, cloud cover tends to be higher in the morning and afternoon, and the times of satellite overpass are generally in the middle of the day. Caution should be exercised, however, in generalizing the comparison results/statistics. In high latitude regions, for example, one expects a reduced bias because a target is generally observed several times during the day by individual satellites. It is desirable to extend the evaluation to high latitude regions. Nonetheless, the results obtained at the COVE site indicate that the accuracy on the PAR products is suitable for large-scale studies of aquatic photosynthesis.

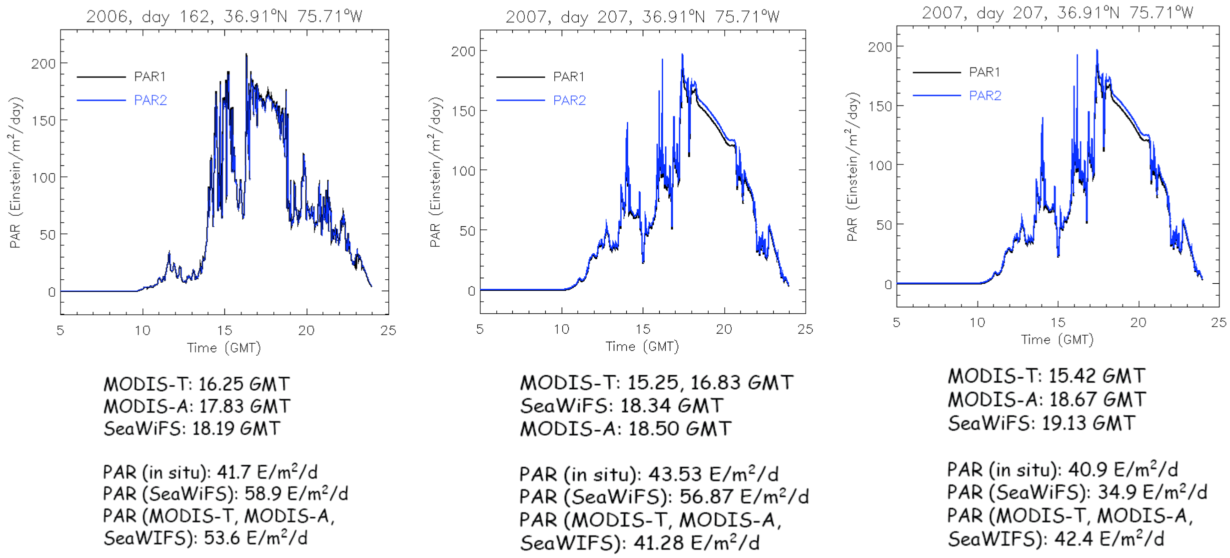
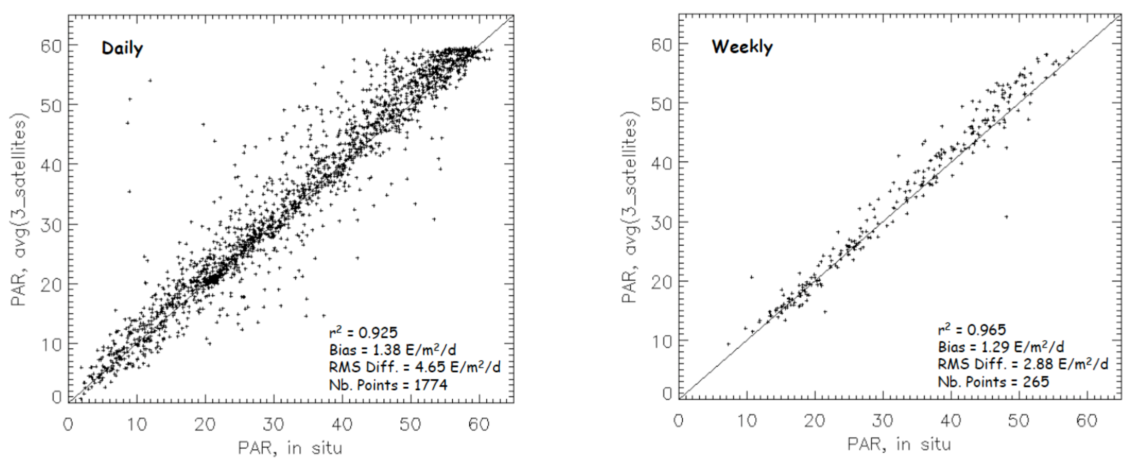


Figure 2*: Measured surface PAR in typical cloudy situations at the COVE site. Combining estimates from three instruments reduces the differences with in situ measurements.*



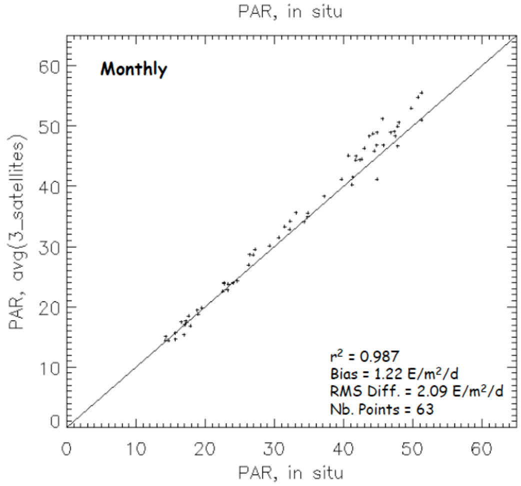


Figure 3*: Comparison between estimates of daily, weekly, and monthly PAR at the COVE site. The estimates are obtained by combining individual estimates from SeaWiFS, MODIS-Aqua, and MODIS-Terra. Using three instruments, the performance is improved compared with that of individual satellites, with biases and RMS differences in monthly values reduced from 1.8-2.2 to 1.2 E/m²/d.*

4. GENERATION OF A CONSISTENT LONG-TERM CLIMATE RECORD

Not all the various ocean-color instruments used to estimate PAR have operated during the entire period of interest, i.e., 1997 to present. SeaWiFS provided data from September 1997 to December 2010. MERIS, MODIS-Terra, and MODIS Aqua started operations in December 1999, March 2000, and July 2002, respectively. For a given instrument, gaps in the time series data may also exist (due to malfunction, tests, etc.). On the other hand, evaluation at the COVE site (see Section 2.2) has revealed biases between PAR estimates from individual instruments. In order to generate a consistent time series of PAR from 1997, the spatial and temporal biases need to be determined.

This was accomplished using 5 years of SeaWiFS, MODIS-Aqua, and MODIS-Terra PAR imagery from 2005 to 2010 (MERIS was excluded in the analysis). The PAR values from individual instruments were compared with those from combining three instruments. Monthly maps of average differences were computed at 9 km resolution. These maps were then used to correct the estimates from individual instruments and produce a 13-year time series of PAR imagery from 1997 to 2010. Figure 4, top displays for January and July histograms of differences between monthly PAR estimates from individual instruments, combinations of two instruments, and three instruments. The differences range from about -4 to 4 $E/m^2/d$. They are generally positive for SeaWiFS, and negative for MODIS-Aqua and MODIS-Terra. After correcting for average differences, the histograms are centered on zero for all the instruments and their combinations (Figure 4, bottom).

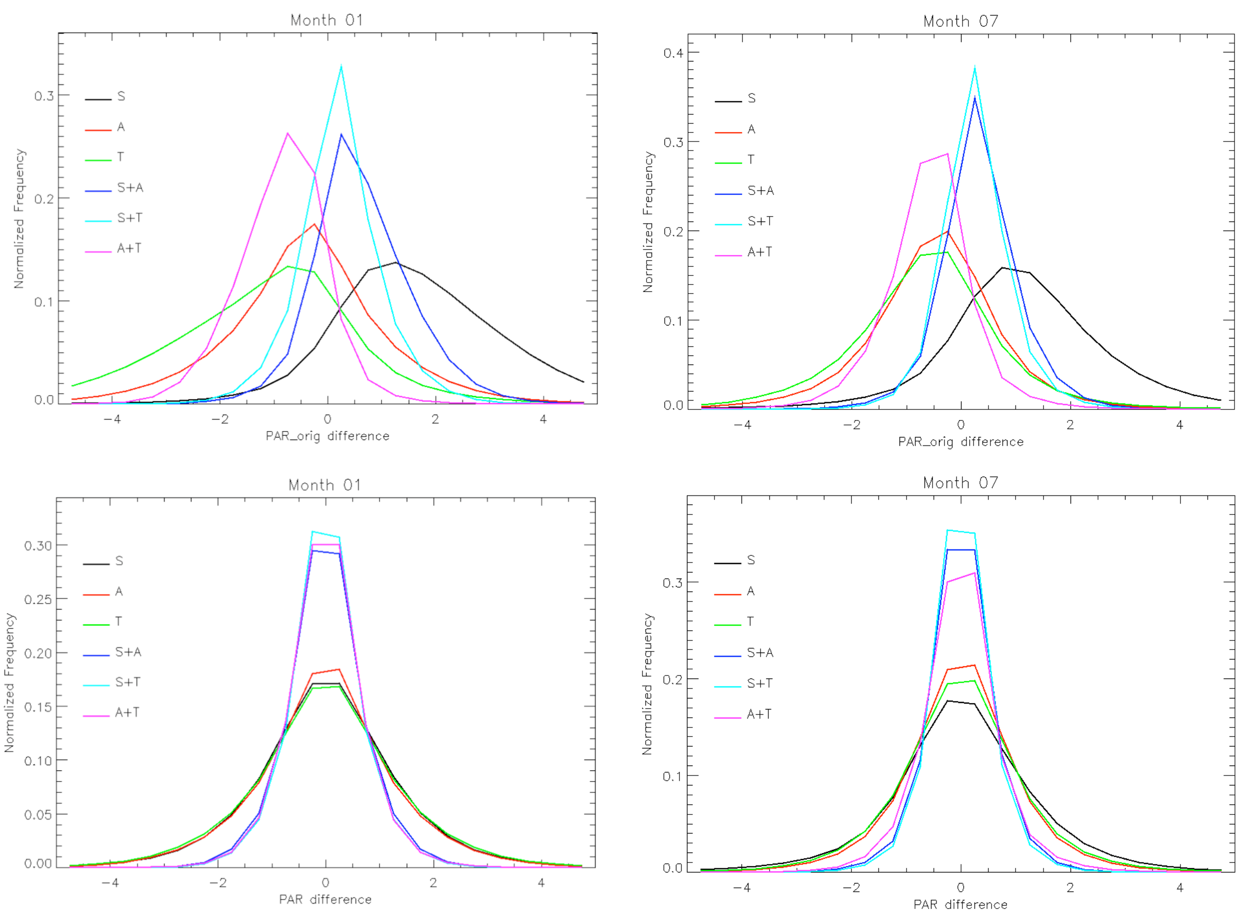


***Figure 4**: (Top) Histograms of January and July differences between PAR derived by individual or two instruments and PAR derived by three instruments. (Bottom) Same as (Top), but after correction of biases. The histograms are computed with global PAR data from January 2005 to December 2010. Differences are expressed in $E/m^2/d$.*

Figures 5, 6, and 7 display some examples of PAR imagery obtained from one instrument and any of three (i.e., all available) instruments. Spatial coverage is definitely improved in the MODIS-Aqua daily imagery by combining the available instruments (Figure 5). The missing values in the weekly SeaWiFS imagery are completely filled in the merged imagery (Figure 6). The monthly PAR product from MODIS-Terra, however, is very similar to the merged product (Figure 7). No biases are discernable. At this time scale, adding information from additional instruments may not result in significant improvements.

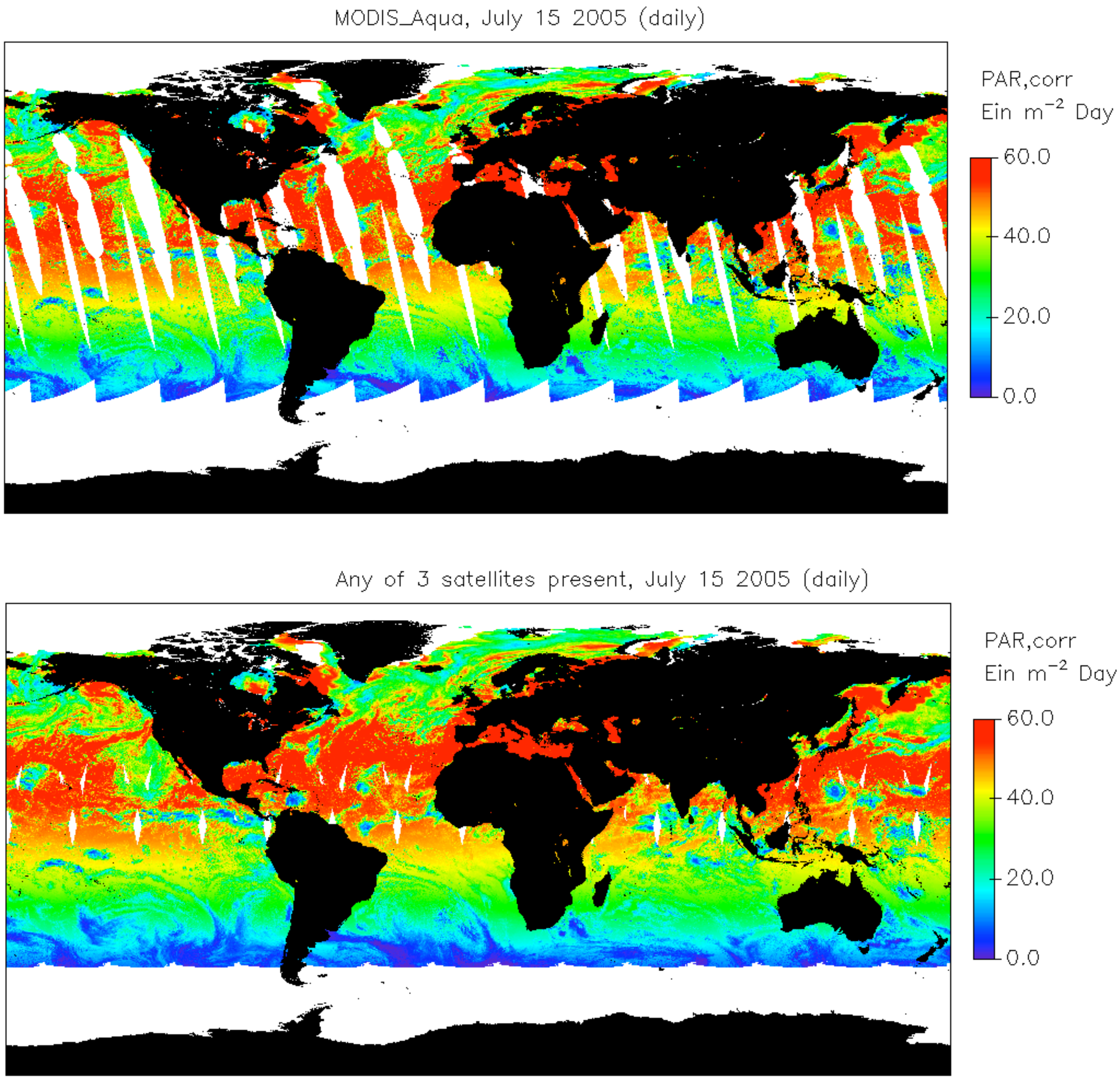


Figure 5*: (Top) Daily PAR obtained from MODIS-Aqua for July 15, 2005. (Bottom) Daily PAR obtained from SeaWiFS, MODIS-Aqua, and MODIS-Terra (all available instruments are used). Data from individual instruments are corrected for biases with respect to three instruments.*

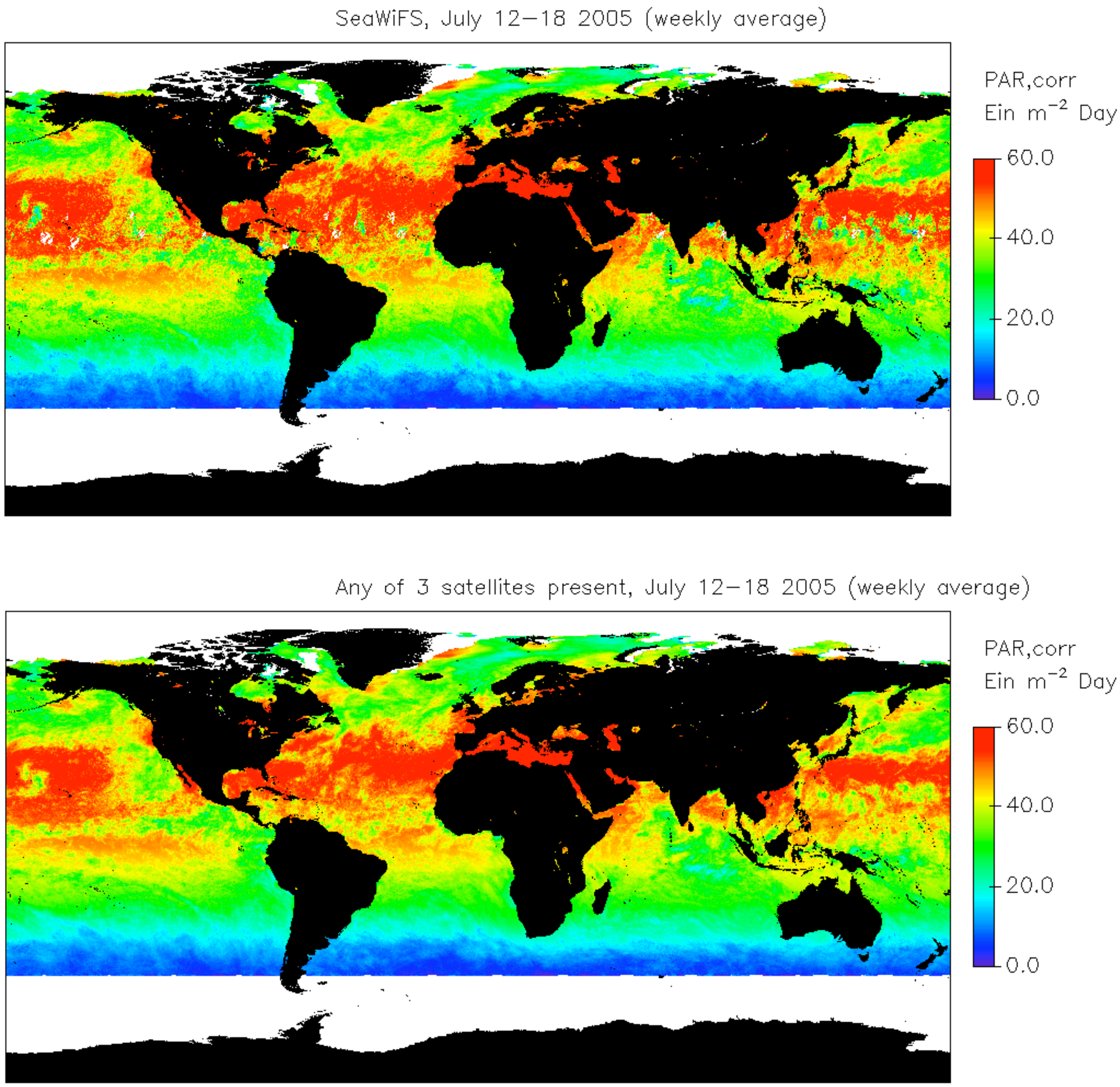


Figure 6*: (Top) Weekly PAR obtained from SeaWiFS for July 12-18, 2005. (Bottom) Weekly PAR obtained from SeaWiFS, MODIS-Aqua, and MODIS-Terra (all available instruments are used). Data from individual instruments are corrected for biases with respect to three instruments.*

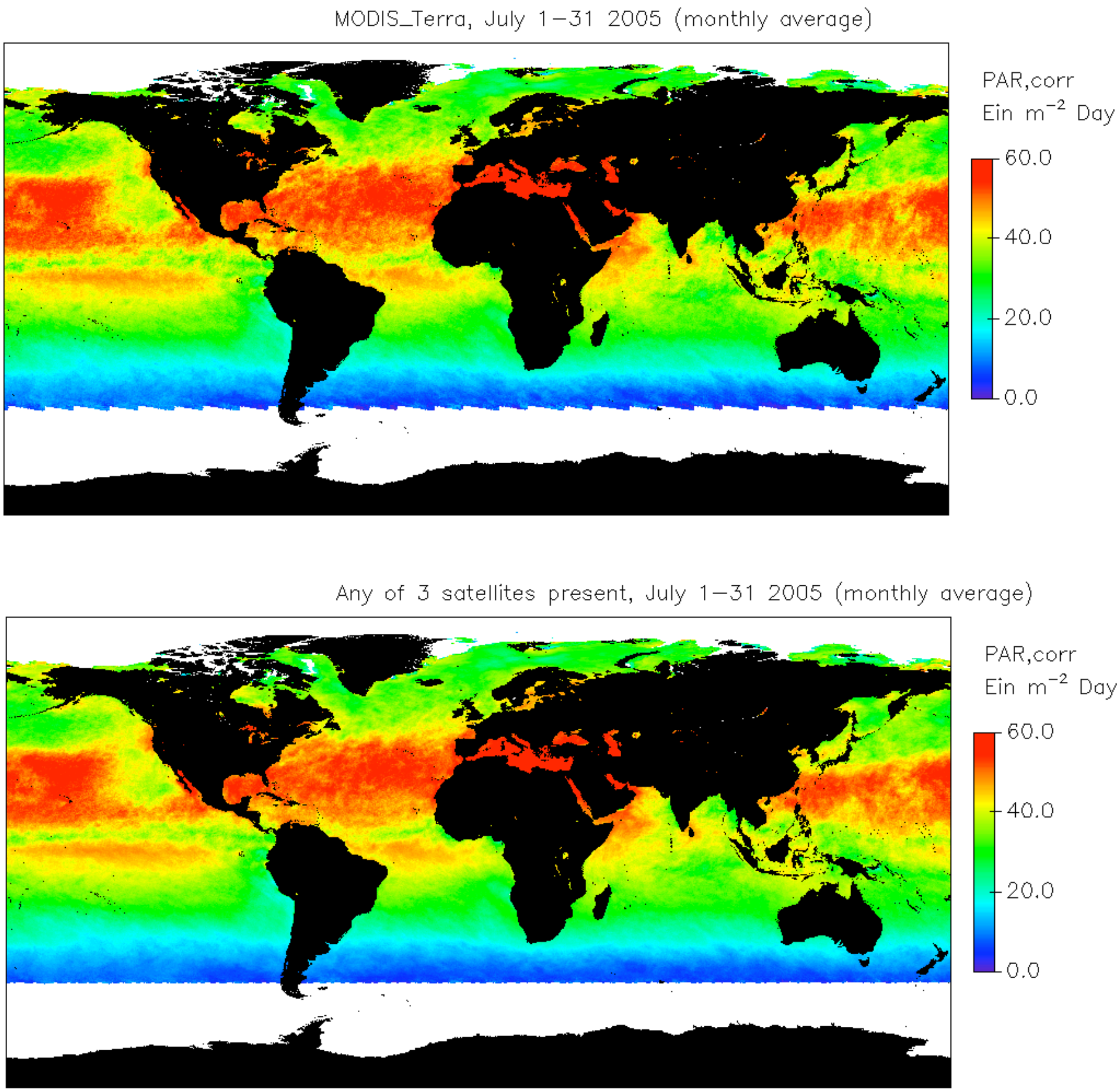


Figure 7*: (Top) Monthly PAR obtained from MODIS-Terra for July 2005. (Bottom) Monthly PAR obtained from SeaWiFS, MODIS-Aqua, and MODIS-Terra (all available instruments are used). Data from individual instruments are corrected for biases with respect to three instruments.*

Figure 8 displays a time series, September 1997-present, of PAR at two geographic locations, one in the Equatorial pacific, the other in the North Atlantic. The PAR imagery at 9 km resolution has been interpolated to the respective locations. Seasonal variability is substantially different at the two locations, largely due to changes in solar zenith angle, with larger amplitude in the North Atlantic. Daily values are generally lower in the North Atlantic, even during summer. Such time series provide the means to investigate inter-annual variability of oceanic primary production and allow numerical modeling of biogeochemical impacts of climate change.

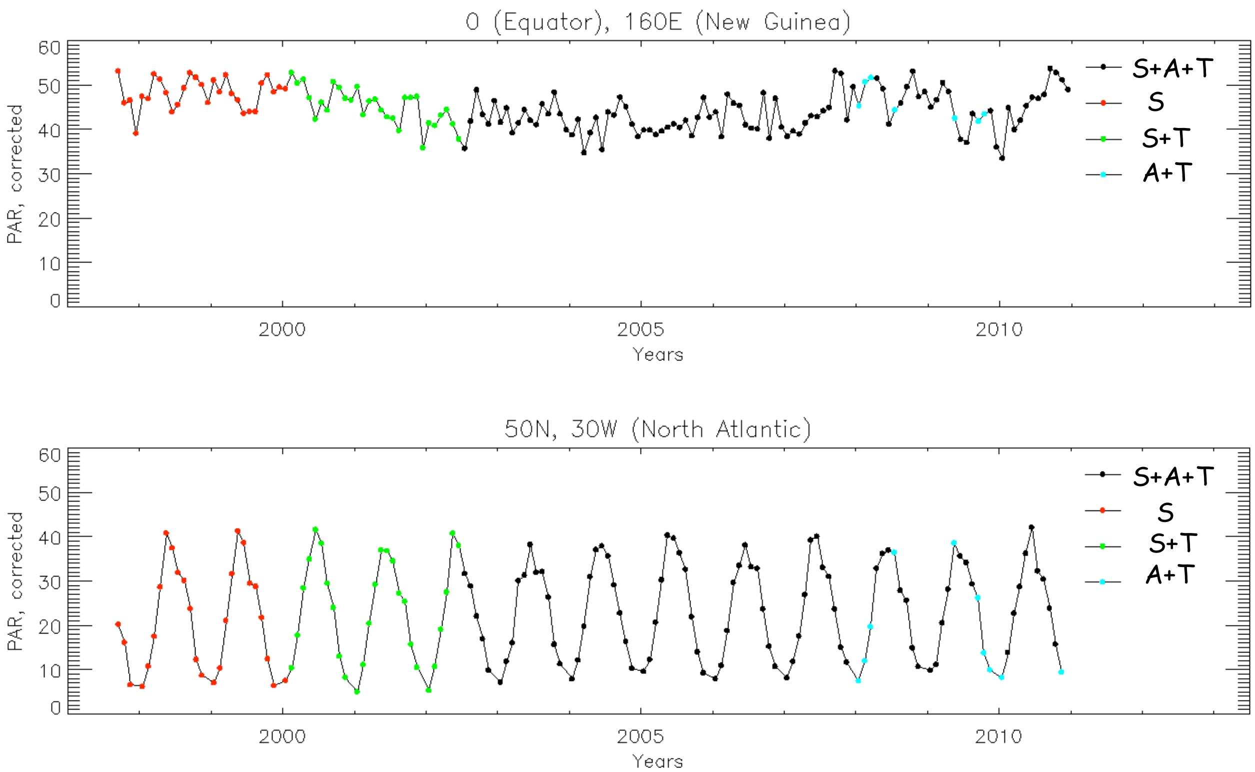


***Figure 8**: Time series of monthly PAR data obtained from one, two, or three instruments. (Top) Equator and 160 E; (Bottom) 50 N and 30 W. The values obtained by individual instruments are corrected for biases with respect to three instruments.*

An example of correlative analysis is given in Figure 9, which displays the 1997-2011 time series of PAR, sea surface temperature (SST) and chlorophyll-a concentration ([Chl-a]) anomalies with respect to the average seasonal cycle at the Equator and the 180-degree longitude (Western Pacific). The various time series are strongly correlated, with negative PAR and [Chl-a] anomalies and positive SST anomalies during El Niño events and the reverse during la Niña events (Figure 9, top left, top right, and bottom left). One could therefore interpret the [Chl-a] changes as the consequence of PAR and SST changes. Indeed, a lower PAR and higher SST may be associated to less primary production and vice versa. The maximum correlation, however, does not occur at the time lag of zero for the PAR and [Chl-a] anomalies (Figure 9, bottom right). This only occurs for PAR and SST, which vary in phase. The [Chl-a] changes precede the PAR changes by one month, suggesting that the PAR anomalies do not drive the [Chl-a] anomalies at the location considered. In the Western Pacific, light is not a limitation to primary production, and changes in thermal structure, therefore availability of nutrients, or advection may play a dominant role. Further investigation is necessary to elucidate the causes of [Chl-a] variability in the region.

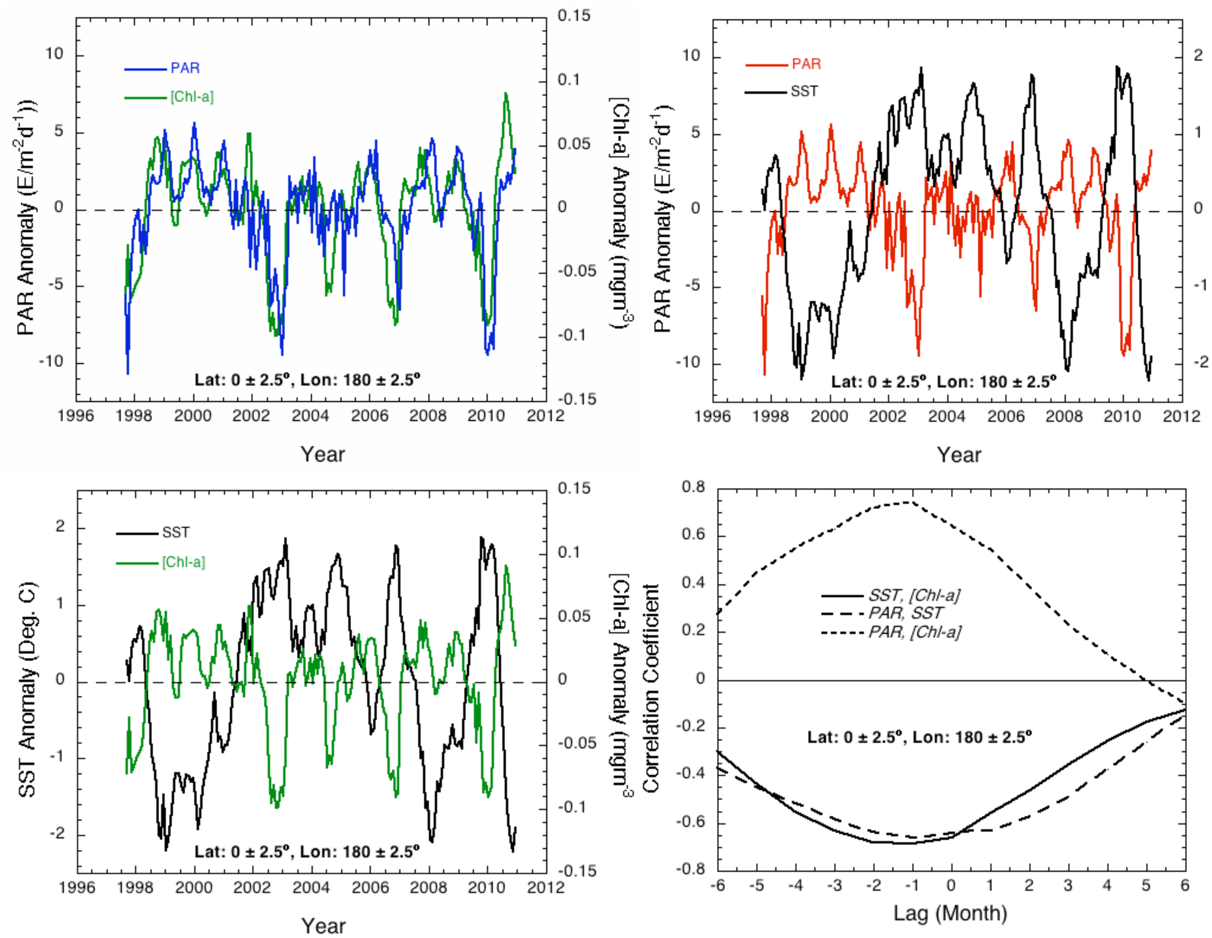


Figure 9*: Time evolution of monthly PAR, SST, and [Chl-a] anomalies in the Western Equatorial Pacific during 1997-2010 and correlation coefficient between various time series.*

5. EXTENSION TO UV IRRADIANCE

Ultraviolet (UV) radiation (280-400 nm) affects carbon cycling (capture, storage, and release). Enhanced UV irradiance may inhibit phytoplankton photosynthesis, increase ocean transparency (photo-oxidation of CDOM), increase bioavailability of nutrients, etc. Cloud properties (extinction coefficient, asymmetry factor) are similar in the UV and PAR spectral ranges, i.e., effects of clouds on UV irradiance may be estimated from effects in the PAR range, making it straightforward to extend the PAR algorithm and estimate UV irradiance.

This is illustrated for UV-A (320-400 nm) in Figure 10, which displays the relation between cloud albedo in the UV-A and PAR spectral ranges (left panel) and the relation between cloud transmittance in the UV-A and PAR spectral ranges (right panel). Various cloud types (cirrus, stratus, cumulus), cloud optical thicknesses (0, 5, 10, 50), and solar zenith angles (0, 30, 45, 60, and 75 degrees) are considered in the computations. In the absence of molecules, (Figure 10, left), the relation is fairly unique between cloud albedo in the two spectral ranges. This is not the case when molecules are present, due to the coupling between cloud droplets or crystals and molecules, and the relation between cloud transmittance in the two spectral ranges depends on the type of clouds and their location in the vertical. This indicates that de-coupling the clear atmosphere from clouds, as it is done in the PAR algorithm, may introduce significant errors in the estimation of UV irradiance.

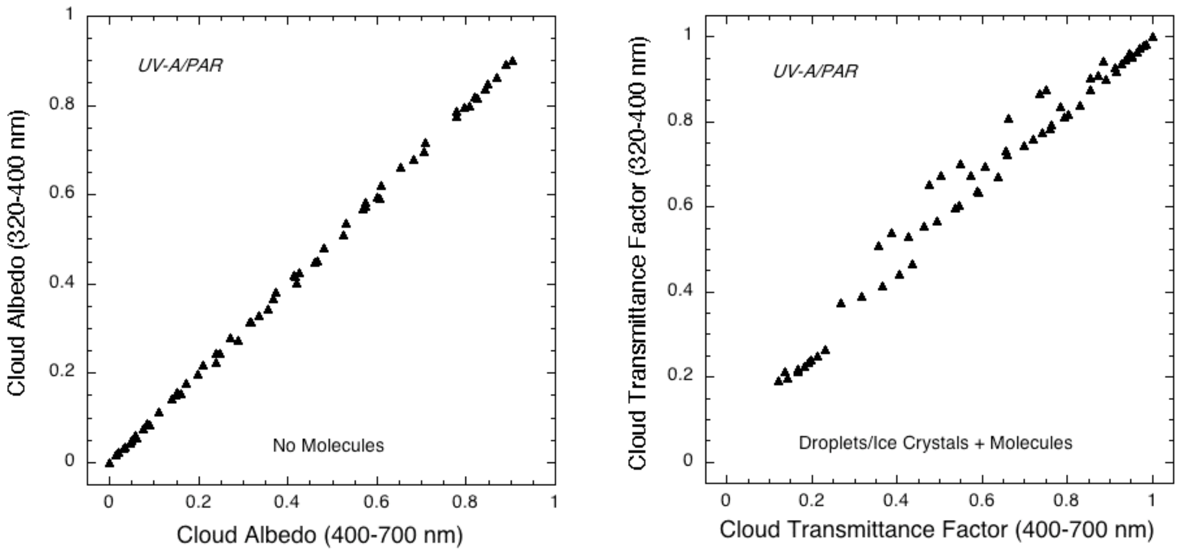


***Figure 10**: Cloud albedo (left) and transmission factor (right) in the UV-A and PAR spectral range for various cloud types (stratus, cumulus, and cirrus), optical thicknesses (0, 5, 10, 50), and solar zenith angles (0, 30, 45, 60, and 75 deg.).*

6. CONCLUSIONS

A global, 13-year record of PAR at the ocean surface (9-km resolution) has been generated from SeaWiFS, MODIS-Aqua, and MODIS-Terra data. Observations by individual instruments, combinations of two instruments, and three instruments are considered in the calculations. Spatial and temporal biases between estimates from one, two, or three instruments are determined and corrected, resulting in a consistent time series for variability studies. Uncertainties are quantified on daily, weekly, and monthly time scales for the various instrument combinations from comparisons with in situ measurements. They indicate that the PAR products are suitable for large-scale studies of aquatic photosynthesis. PAR monitoring will continue with current and future satellite ocean-color sensors (e.g., VIIRS), and the methodology will be extended to generating UV-A and UV-B irradiance.

ACKNOWLEDGMENTS

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